

Innovative Seismic Solutions for Multi-Storey LVL Timber Buildings

Alessandro Palermo
Department of Structural Engineering
Politecnico di Milano
Milan, Italy

S. Pampanin, M. Fragiaco, A.H. Buchanan, B.L. Deam
Department of Civil Engineering
University of Canterbury
Christchurch, New Zealand

Summary

The paper describes an extensive experimental program at the University of Canterbury, for the development of new structural systems and connections for multi-storey laminated veneer lumber (LVL) timber buildings in earthquake-prone areas. The proposed innovative ductile timber connections are conceptually similar to recent seismic solutions successfully developed for precast concrete multi-storey buildings. The paper gives an overview of the research program, and the results of quasi-static cyclic tests on frame subassemblies, including exterior beam-column joints and cantilever columns, as well as pseudo-dynamic tests on cantilever columns. The experimental results showed significant dissipation of hysteretic energy, good self-centering capacity and no appreciable damage of the structural elements, confirming the expected enhanced performance of the proposed structural systems.

1. Introduction

Innovative jointed ductile connections, based on post-tensioned precast concrete building systems (U.S. PRESSS Program, coordinated at the University of California, San Diego [1]) extended subsequently to steel construction, are proposed for timber seismic resisting frame and wall systems [2], with emphasis on Laminated Veneer Lumber (LVL) for multi-storey buildings.

In jointed ductile connections, prefabricated structural elements are connected by unbonded post-tensioning, so that the inelastic seismic demand is accommodated in the connection itself through the opening and closing of an existing gap, while the structural elements are kept within the elastic range with very limited damage. In addition, permanent residual deformations are negligible due to the inherent re-centering capability provided by the unbonded tendons. These structural systems are seen as superior to their “monolithic” counterparts such as cast-in-place reinforced concrete, welded or bolted steel construction, or fully bolted, nailed or glued timber construction.

A particularly efficient structural solution is provided by the “hybrid” system, so named for the combination of self-centering properties (unbonded tendons plus axial load) plus energy dissipation (mild steel or additional dissipation devices). As a result, “controlled rocking motion” governs the behaviour, characterized by a peculiar “flag-shaped” hysteresis loop (Fig. 1). A high-performance system can thus be obtained, which can undergo large inelastic displacements similar to monolithic construction, while limiting structural damage and assuring full re-centering capability after the seismic event. The hybrid concept is extended to LVL solutions for multi-storey frame or shear wall buildings in this paper. It is worth noting that the proposed LVL solutions are not significantly affected by the tensile strength of the material, so they may possibly be used with other wood-based materials after suitable testing.

Several types of moment-resisting connections and structural details have been described in the literature for timber frames and walls (i.e. nailed, bolted or dowel connections, glued or epoxied

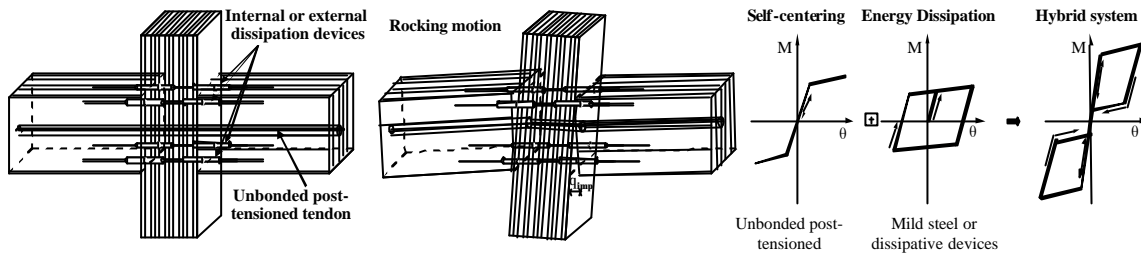


Fig 1 Application of hybrid concept to LVL beam-column subassemblies and idealized flag-shape hysteresis loop

steel rods). Different forms of inelastic behaviour lead to different levels of ductility and structural performance. For example, typical pinching behaviour can be observed in the hysteresis response of nailed walls [3] and frames [4] (Figure 2a), while more stable hysteresis loops and limited stiffness degradation can be found with epoxied rods in glulam (Figure 2b). However, as with monolithic concrete or steel, excessive residual deformations and high repair costs would be expected after an earthquake, even if the building has been designed according to current codes. Recent performance-based seismic design and assessment procedures have emphasized the importance of limiting residual deformations, as a fundamental indicator of structural and non-structural damage [5], [6].

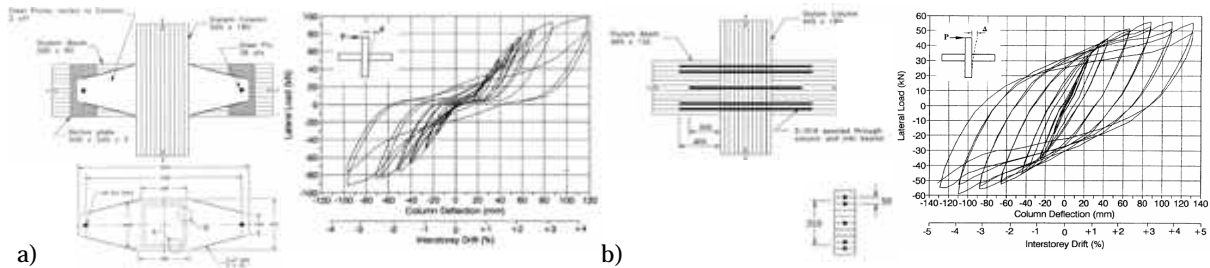


Fig 2 Layout and hysteresis loop for frame systems: a) multiple-nailed connection; b) epoxied rods glulam solution Buchanan & Fairweather [4]

2. Overview of the research program

An extensive research program has been planned to investigate the seismic performance of innovative ductile jointed connections for multi-storey LVL buildings, with seismic loads resisted by frames and/or walls. These concepts will be applied to 2-D and 3-D frames, structural walls and dual systems (coupled frame and wall systems), with the intent of developing feasible solutions for broad and extensive applications in the worldwide construction industry. The program will involve comprehensive numerical and experimental investigations of subassemblies and whole lateral force resisting systems. Finally, critical comparison will be made with the response of typical “damageable” solutions (monolithic construction). The program is divided into three phases:

Phase one, started under a joint agreement between the University and Carter Holt Harvey, emphasises the conceptual development, design and construction, followed by tests under a quasi-static loading regime. The study includes beam-column joints, column-to-foundation and wall-to-foundation specimens (Fig. 3). Current testing includes uni- and bi-directional quasi-static tests under lateral loading on several beam-column joint subassemblies and cantilever columns in 2-D and 3-D configurations. The main variables are the use of unbonded post-tensioned tendons only, or in combination (hybrid systems) with internal or external energy dissipaters of different typologies (elasto-plastic, friction, viscous). For frame systems, solutions based on either straight or parabolic tendon profiles will be considered, depending on the expected seismicity of the region.

In the second phase of the research, particular attention will be given to the global seismic performance of LVL systems with alternative ductile jointed connections. The seismic behaviour of

coupled wall systems (with or without energy dissipation devices), multi-storey seismic-resisting frames and dual systems will be investigated through quasi-static cyclic tests and parametric numerical analyses.

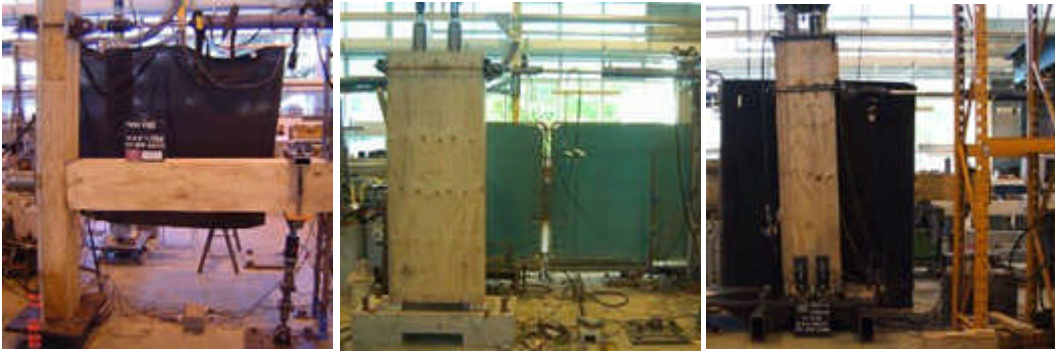


Fig 3 Exterior beam-column, wall-to-foundation, column-to-foundation specimens

In the third phase, displacement incompatibility between the lateral-load resisting systems and the floor diaphragms will be investigated. Alternative floor solutions, either timber or composite timber-concrete with or without prestressing, will be considered with the aim of developing adequate connections between floors and the adjacent lateral load resisting system, and of limiting the slab damage on due to possible elongation effects.

The design, construction and large scale testing of a multi-storey building super-assembly comprised of frames, walls and floors will represent the ultimate validation of the proposed solutions. Simplified design provisions for the next generation of codes will also be developed based on appropriate modifications of well-established methods for precast concrete [7], [8]. The program will also validate and refine existing analytical procedures from the literature for precast concrete systems [9], [10] with modifications to account for the peculiarities of LVL timber.

3. Quasi-static cyclic testing

In the first phase of the research project, quasi-static cyclic tests were carried out on frame subassemblies, including exterior beam-column joints, and column-to-foundation connections, as well as on shear wall systems. Focus in this paper will be given to the response of frame subassemblies, while further details on the response of wall system can be found elsewhere [11]. The geometry of the specimens and corresponding test set-ups of the beam-column joint and cantilever column subassemblies are shown in Fig. 4.

Table 1 Material properties from tests on small specimens

Materials	Beam-column joint, column specimen	
LVL Hy90, parallel to the grain: f_c , E_c	28 MPa,	9.0 GPa
LVL Hy90, perpend. To the grain: f_p , E_p	10 MPa,	9.0 GPa
LVL Hy63/105, parallel to the grain: f_c , E_c	34 MPa,	13.2 GPa
LVL Hy63/105, perpend. to the grain: f_p , E_p	12 MPa,	13.2 GPa
Mild steel bars, i.e. internal dissipaters: f_{sy}	340 MPa (yield)	
7-wire pre-stressing strand ($A_{pt}=99\text{mm}^2$): f_{pv}	1530 MPa (yield), 1870 MPa (0.2% proof stress)	

The horizontal load was applied at the top of the test-specimens, representing the point of contraflexure (zero moment) in the prototype frame or wall structure subjected to lateral loading. A constant level of column axial load of 120kN, simulating gravity loads, was applied to the beam-column subassemblies through an external actuator. In the column-to-foundation specimens the initial post-tensioning of the two tendons passing through the foundation (Fig. 4) includes the axial force due to gravity load. The loading protocol is characterized by a series of three cycles of increasing top-column displacement applied through the horizontal hydraulic actuator, following the acceptance criteria for innovative jointed precast concrete frame systems proposed by the ACI

T1.1-01, ACI T1.1R-01 documents [12]. The material properties are reported in Table 1. The significant strength difference of the LVL material in the directions parallel and perpendicular to the grain (up to three times) can be easily seen. This becomes a limiting consideration for the beam-column subassembly where the face of the column is in contact with the end of the beam, while there is no problem for cantilever columns or walls because the rocking LVL end-grain surface acts on the steel foundation.

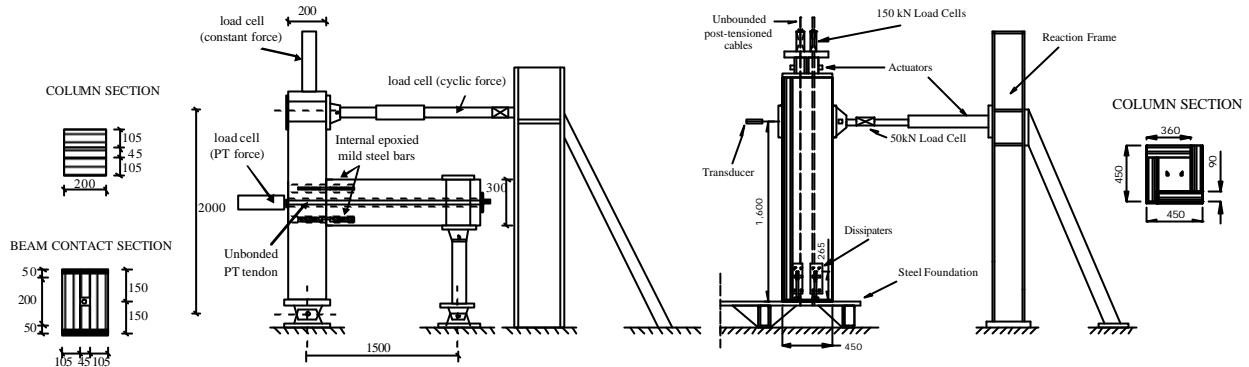


Fig 4 Test-set up and geometry for exterior beam-column joint and cantilever column specimens

3.1 Beam-column subassemblies

For sake of brevity, quasi-static cyclic tests on three beam-column joint results are described here; two unbonded post-tensioned-only solutions and two hybrid solutions with external and internal dissipaters. More details can be found in Palermo et al. [11]. Fig. 5 (left side) shows details of the internal dissipaters which consist of 10mm diameter (grade 340) deformed bars top and bottom, machined to 8mm to create a fuse along an unbonded 50mm length. The four external dissipaters each consist of 8mm bars encased in steel tubes with epoxy to prevent buckling (Fig. 5 right side). Variations of initial prestressing have been considered; $0.4 f_{py}$ and $0.6 f_{py}$ for the two unbonded-post-tensioned-only specimens and $0.8 f_{py}$ and $0.6 f_{py}$ for the hybrid solutions with internal and external dissipaters.

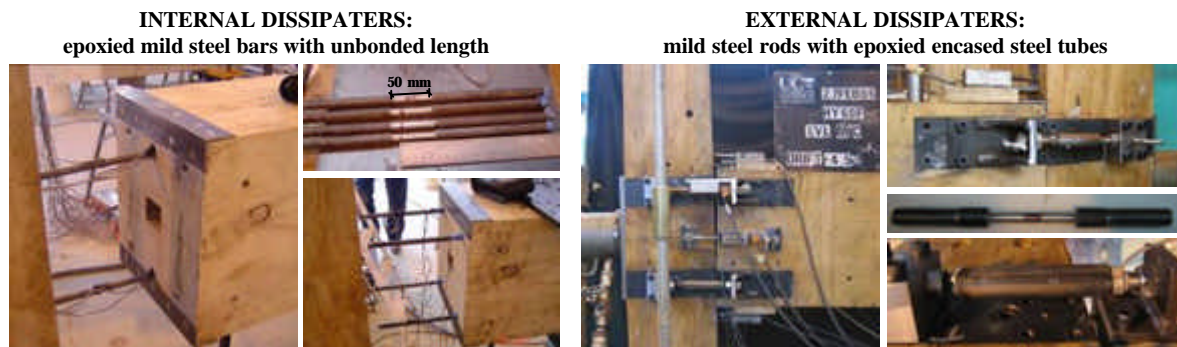


Fig 5 Internal and external dissipaters and construction details

Figure 6 illustrates the experimental response in terms of lateral force vs. inter-storey drift (ratio of top-displacement and column height). A full re-centering capacity has been provided by all the solutions, the different levels of strength and additional dissipation capacity depending on the combination of initial prestressing and amount of dissipation contribution [8]. An appropriate design of the ratio between the self-centering moment contribution and the energy-dissipating moment contribution, also referred to as λ -parameter [8], can govern the overall behaviour. When referring to the unbonded post-tensioned solution, a non-linear elastic hysteresis is observed, as expected, with minor amount of hysteretic dissipation provided by the local non-linear behaviour of

the LVL material at the column contact section, loaded in compression perpendicular to the grain. It is worth noting that the loss of linearity or “knee-point”, similar to the yielding point of a dissipative traditional connection, is in this case due to geometrical non-linearity, i.e. a reduction of section stiffness due to a sudden relocation of the neutral axis position. The reduced stiffness after the equivalent “yielding” corresponds to an increase in moment capacity primarily due to the elongation of the tendons. To preserve the column specimen from possible damage due to compression crushing perpendicular to the grain, the test was interrupted at 2.75% drift.

Enhanced performance is highlighted by the two hybrid specimens, as represented in Figures 6b, 6c, where in addition to the self-centering capacity provided by the tendon a certain amount of dissipation capacity is given by the external or internal dissipaters. In both the hybrid solutions, the equivalent yielding point corresponds to the actual yielding of the dissipation devices, observed at 0.8% inter-storey drift. During repeated cycles at a medium-high level of drift, some onset of stiffness degradation was observed for the solution with internal dissipaters, probably due to bond deterioration between the deformed mild steel bars and LVL through the epoxy, while more stable flag-shape hysteresis loops are observed for the external dissipaters.

As shown in Figure 7, no visible damage occurred in the beam or the column up to the third cycle at 4.5% drift. In the hybrid specimens, failure of the internal dissipaters occurred at that point due to the repeated cycles after buckling within the unbonded length. The tests of the hybrid specimens were stopped at that time to prevent possible yielding of the tendons.

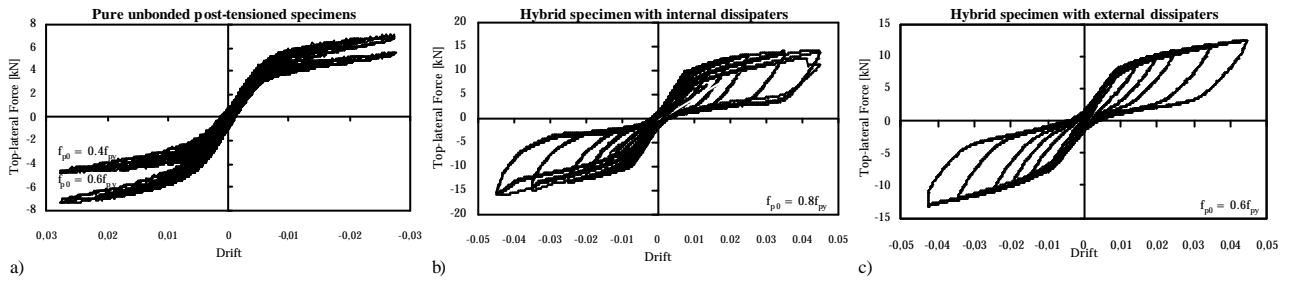


Fig 6 Lateral force-drift curve: a) pure unbonded post-tensioned solution; b) hybrid solution with internal dissipaters; c) hybrid solution with external dissipaters

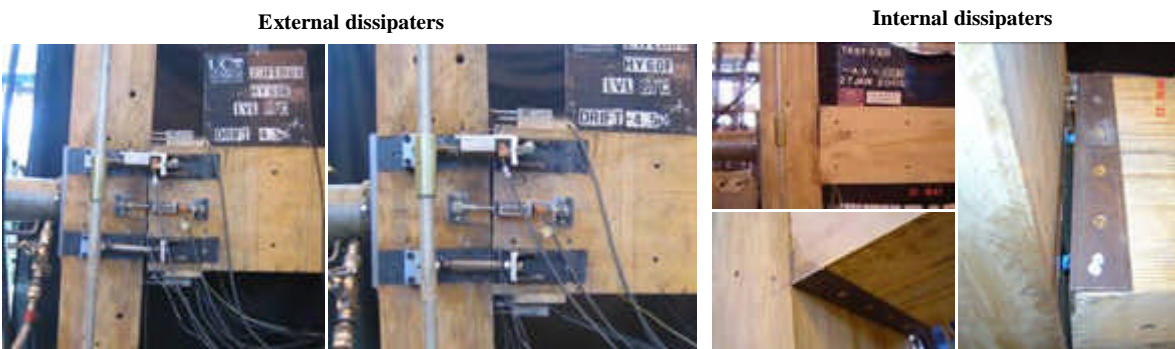


Fig 7 Hybrid solution: appearance of the specimen at 4.5% drift

3.2 Column-to-foundation specimens

As part of the investigation of frame subassemblies, a series of quasi-static cyclic tests on cantilever columns connected to the foundation were carried out. In particular the tests results related to three unbonded post-tensioned solutions and one hybrid solution with external dissipaters. Similar solutions to those previously described for the beam-column joints, were adopted for the dissipaters (Figure 9) in the cantilever column specimen; the top end of each external dissipater is connected to an external steel case fixed to the LVL column and the bottom end is fixed to the steel foundation.

The column specimen illustrated in Figure 9 has been used for several tests without showing evident damage. Figure 8a shows the experimental response in terms of lateral force vs. drift of three unbonded post-tensioned-only specimens with three different levels of initial post-tensioning (0.3 , 0.4 and $0.5 f_{py}$) under the same loading protocol. The behaviour is very similar to the unbonded post tensioned beam-to-column solutions presented in paragraph 3.1. However, the hysteretic dissipation due to the non-linear behaviour of the material, is negligible here when compared to the beam-to-column subassembly, since the rocking surface consist of LVL parallel to the grain in contact with steel. As a consequence, the “knee-point” due to geometrical non-linearity is more clearly delineated due to a more sudden relocation of the neutral axis position. The tests have been interrupted at 4.5% drift without no evident damage, only in order to preserve the bottom of the LVL column test specimen from possible crushing damage and to prevent yielding of the two tendons. The hybrid specimens comprise two unbonded post-tensioned tendons with initial post-tensioning of $0.5 f_{py}$ and two external dissipaters ($\phi 10$ mm, grade 340, deformed bars, machined down to $\phi 8$ mm) placed on each side, with an effective length of 130 mm. The force-drift curve of Figure 8b shows very stable flag-shaped hysteresis behaviour. No apparent stiffness degradation can be observed in the hybrid solution thanks to the absence of bond degradation in the external dissipation devices. Finally, Figure 9 shows no visible damage after the third cycle of 4.5% drift for both the unbonded post-tensioned-only and the hybrid solutions.

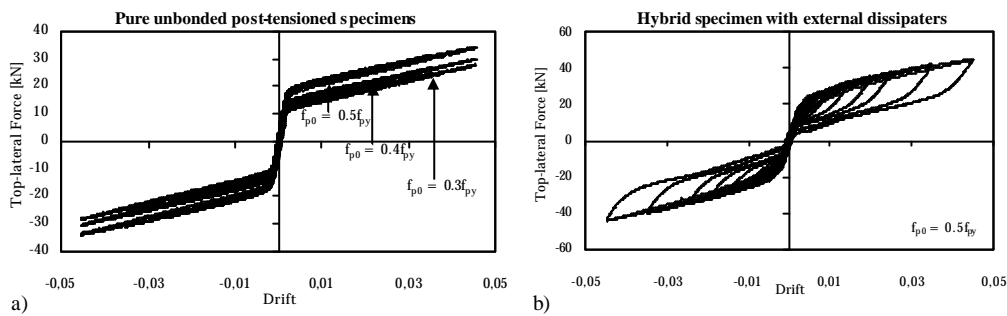


Fig 8 Lateral force-drift response of cantilever columns: a) unbonded post-tensioned-only solution; b) hybrid solution with external dissipaters



Fig 9 Unbonded post-tensioned (left) and hybrid (right) column specimen at 4.5% drift

4. Pseudo-dynamic testing on cantilever column-to-foundation specimen

A series of pseudo-dynamic tests was carried out to simulate slow motion (thus without strain rate effects) dynamic response of a structural system subjected to an earthquake input ground motion, on cantilever column-to-foundation connections in both unbonded post-tensioned-only and hybrid configurations. The effects of various levels of initial post-tensioning and different additional dissipation capacity on the dynamic response were investigated and provided valuable complementary information to that obtained from the quasi-static tests. Due to space limitations, this paper describes only the results of the pseudo-dynamic tests on one unbonded post-tensioned-only solution (initial post-tensioning $0.5f_{py}$) and one hybrid solution with same level of post-

tensioning and two external dissipaters per side ($\phi 10$ mm bars machined down to $\phi 8$ mm as described in par. 3.2.).

As part of the required information to solve the equation of motion of the SDOF system within the pseudo-dynamic algorithm, an equivalent mass of $45 \text{ kN s}^2/\text{m}$ was assumed, corresponding to the expected gravity load (dead load plus a portion of the live load) for the tributary area of a column within a one storey timber building. An equivalent viscous damping of 5% was adopted. Figure 10 shows the response of the two solutions under a recorded Loma Prieta accelerogram (Table 2) in terms of a drift time-history and a force-displacement envelope. In order to assure adequate inelastic response and re-centering capability, the hybrid system, having additional strength and dissipation capacity provided by the dissipaters, was subjected to a 50% higher intensity of the selected record. Valuable confirmation of the results of quasi-static cyclic tests previously presented is obtained: a full re-centering capability is maintained regardless of the intensity of the earthquake or of the partial asymmetry of the response and the amount of additional dissipation. Furthermore, similar levels of drift demand (in the order of 2%) were achieved, in spite of the higher intensity of the ground motion thanks to the additional strength and dissipation contribution provided by the external dissipaters.

Table 2 Characteristics of the Loma Prieta earthquake record adopted

Year	Mw	Station	R_{closest} [km]	Soil Type (NEHRP)	Duration [s]	Scaling Factor	Scaled PGA (g)
1989	6.9	Hollister Diff. Array	25.8	D	39.6	1.3	0.363

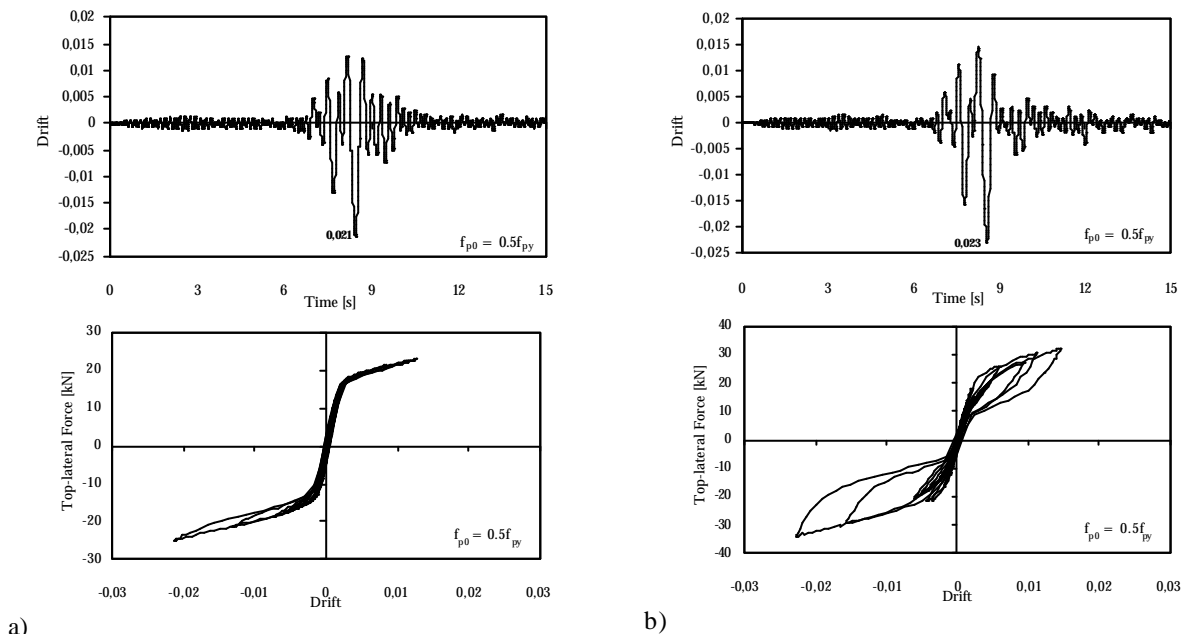


Fig 10 Pseudo-dynamic test results of a) unbonded post-tensioned solution b) hybrid solution under Loma Prieta record (at 100% and 150% intensity, respectively): drift history and force-drift

5. Conclusions

The preliminary experimental results of cyclic quasi-static and pseudo-dynamic tests on LVL frame subassemblies (beam-column joints and column-to foundation connections), confirmed the enhanced performance of the jointed ductile or hybrid connections. In all cases, considering different simulations of seismic loading, the tested systems can guarantee high levels of ductility, negligible residual deformations and no significant damage of the structural elements. For buildings with these new structural systems, a significant reduction in repair and downtime (business

interruption) costs can be expected after an earthquake compared to traditional solutions widely used in timber construction (e.g. nailed, bolted or steel dowel connections). There are even greater benefits when sacrificial dissipaters are used because these can be replaced after the earthquake.

Based on these very satisfactory and promising results, further experimental and analytical investigations are currently ongoing for the development of efficient and practical LVL hybrid solutions for multi-storey building systems. Alternative lateral load resisting systems will be considered while investigating refined and alternative arrangements for the tendon profiles, shear keys and energy dissipaters.

6. Acknowledgments

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